

Full determination of transition matrix elements in the $\vec{d}(\vec{p}, pp)n$ reaction

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Abstract

It is shown that in the $d(p, pp)n$ reaction with a colinear geometry and the two outgoing protons in a singlet state, the only two independent T-matrix elements can be determined from spin correlation experiments. These matrix elements are strongly dependent on the deuteron helicity amplitudes, which are expected to vanish for $1.4 fm^{-1} < p < 1.7 fm^{-1}$.

The deuteron structure is fairly well known for relative distances between the neutron and proton larger than $1fm$, which corresponds to internal momenta smaller than $200MeV/c$. At higher momenta the description of the deuteron in terms of two nucleons becomes sensitive to different NN interactions and furthermore the effects of other degrees of freedom, namely baryon resonances and quarks, are likely to arise. In the momentum range of $0.3-1.2GeV/c$ the deuteron helicity amplitudes are expected to vanish. The precise location of these nodes should contain information on the short-range NN repulsion, and on the non-nucleonic degrees of freedom.

Measurements of polarization observables can provide new insight into the deuteron momentum distribution. In particular, we note that the future availability of polarized gas targets makes it possible to perform spin correlation experiments. Recent data [1]-[10] on deuteron breakup at intermediate and high energy, reveals a strong sensitivity to the high momentum behaviour of the deuteron and the NN interaction. In the present letter we consider a particular type of spin correlation experiment in the $d(p,pp)n$ reaction, which is of special interest.

For a coplanar kinematical configuration, the usual experimental configuration, and assuming parity conservation, the number of independent transition matrix elements corresponding to the different spin projections is 24. This number is reduced to 6 if we detect the two outgoing protons with equal momentum, therefore requiring that they are in a spin-singlet state. A further reduction to two independent matrix elements can be achieved in a colinear experiment where the singlet di-proton is detected either in the forward direction $\theta = 0^\circ$ or at $\theta = 180^\circ$. In fact with this geometry the sum of the spin projections along the incident momentum must be equal in the entrance and exit channels.

Thus we are left with two independent T-matrix elements $\langle \vec{k}'; \sigma_n | T | \vec{k}; \sigma_d, \sigma_p \rangle$

$$T_+ = \langle \vec{k}'; \frac{1}{2} | T | \vec{k}; 0, \frac{1}{2} \rangle \quad (1)$$

$$T_- = \langle \vec{k}'; -\frac{1}{2} | T | \vec{k}; -1, \frac{1}{2} \rangle \quad (2)$$

where \vec{k} is the incident proton momentum and \vec{k}' is the di-proton momentum. Here the T-matrix is the solution of the Lippmann-Schwinger equation in the 3-particle C.M. frame. Matrix elements where all the spin projections $\sigma_p, \sigma_d, \sigma_n$ reverse sign are related to T_{\pm} by parity conservation.

The number of independent spin correlation observables in the $\vec{d}(\vec{p}, (pp)_o)n$ reaction can be easily determined using the spin transfer coefficients

$$T_{k_p q_p k_d q_d} = \frac{1}{\sigma_0} \text{Tr} \left(T \tau_{k_p q_p} \left(\frac{1}{2} \right) \tau_{k_d q_d} (1) T^\dagger \right) \quad (3)$$

where $\sigma_0 = \text{Tr}(TT^\dagger)$ is proportional to the unpolarized cross section and $\tau_{kq}(s)$ are the usual spherical spin tensors for spin s . Choosing the z axis along \vec{k} , the invariance under rotations along this axis implies that the non-vanishing $T_{k_p q_p k_d q_d}$ must have $q_p + q_d = 0$. This leaves five observables: the deuteron analysing power $T_{20} = T_{0020}$, T_{1010} , T_{111-1} , T_{112-1} and σ_{unpol} (the unpolarized cross section). However only four are independent since they are bilinear forms of just two amplitudes T_+ and T_- :

$$\sigma_0 = 2(|T_-|^2 + |T_+|^2) \quad (4)$$

$$\sigma_0 T_{20} = 2\sqrt{2} \left(\frac{1}{2} |T_-|^2 - |T_+|^2 \right) \quad (5)$$

$$\sigma_0 T_{1010} = -\sqrt{\frac{3}{2}} |T_-|^2 \quad (6)$$

$$\sigma_0 T_{111-1} = 2\sqrt{3}Re(T_+T_-) \quad (7)$$

$$\sigma_0 T_{112-1} = i2\sqrt{3}Im(T_+T_-) \quad (8)$$

In fact from eqs(4),(5) and (6) we get the relation:

$$T_{20} = -(\sqrt{2} + \sqrt{3}T_{1010}) \quad (9)$$

which can be useful to check that the two protons are in a singlet state, and the colinearity of the experiment. By measuring σ_{unpol} , T_{20} , T_{111-1} , and T_{112-1} we completely determine the matrix elements T_+ and T_- except for an overall phase factor. This is a very rare situation which results from the peculiar spin structure of the reaction $1 \oplus \frac{1}{2} \Rightarrow \frac{1}{2}$ and the adopted geometry.

We represent the initial state in momentum space by

$$|\vec{k}; \sigma_d, \sigma_1 \rangle = \sum_{m=-1}^1 \Phi_{\sigma_d}^m(\vec{p}) |\vec{k}; 1m, \sigma_1 \rangle \quad (10)$$

where

$$\Phi_{\sigma_d}^m(\vec{p}) = \sum_{L=0,2} u_L(p) Y_L^\lambda(\hat{p}) (L\lambda 1m | 1\sigma_d) \quad (11)$$

and u_0 and u_2 represent the deuteron S and D radial wave functions. A colinear experiment is sensitive to the deuteron amplitudes where the nucleons, in the deuteron rest frame, have either the same helicity

$$\phi_+^d(p\vec{e}_z) = \Phi_0^0(p\vec{e}_z) = \frac{1}{\sqrt{4\pi}} [u_0(p) - \sqrt{2}u_2(p)] \quad (12)$$

or opposite helicities

$$\phi_-^d(p\vec{e}_z) = \Phi_{-1}^{-1}(p\vec{e}_z) = \frac{1}{\sqrt{4\pi}} [u_0(p) + \frac{1}{\sqrt{2}}u_2(p)] \quad (13)$$

Following the notation of ref.[11], we now introduce the quantities $\mathcal{A}_{L_fm\sigma_1}^{NN}(\vec{k}_f, \vec{k}_i)$, which are linear combinations of the half-off-shell NN T-matrix elements

$$\mathcal{A}_{L_fm\sigma_1}^{NN}(\vec{k}_f, \vec{k}_i) = \sum_{L_i} \langle L_f, \vec{k}_f | T^{NN} | L_i, \vec{k}_i \rangle \langle L_i | 1m, \sigma_1 \rangle \quad (14)$$

In the above equation $\vec{k}_i(\vec{k}_f)$ is the initial(final) momentum of the interacting pair and $|L_{i,f}\rangle$ represent the eight orthogonal 3-particle spin states $|s_{pp}SM\rangle$, defined in ref.[11]. By detecting the two protons in coincidence we only have to consider $L_f = 7, 8$, where $|7\rangle = |0\frac{1}{2}\frac{1}{2}\rangle$ and $|8\rangle = |0\frac{1}{2} - \frac{1}{2}\rangle$.

The impulse approximation has been successfully applied to the analysis of $d(p, 2p)n$ reactions at intermediate energies and for small recoil momentum of the neutron ($q_n < 200 MeV/c$) [3, 4, 6, 7, 8, 11]. Within this approximation the T matrix in a colinear experiment is given by (we neglect the binding energy of the deuteron)

$$T_{\pm}^{IA}(0^\circ) = \sqrt{2}[\mathcal{A}_{\pm}^{pp}(0, -\frac{\vec{k}}{2})\phi_{\pm}^d(\frac{\vec{k}}{2}) + \mathcal{A}_{\pm}^{np}(-\frac{3}{4}\vec{k}, -\frac{5}{4}\vec{k})\phi_{\pm}^d(\vec{k})] \quad (15)$$

for $\vec{k}' = \vec{k}$ and

$$T_{\pm}^{IA}(\pi) = \sqrt{2}[\mathcal{A}_{\pm}^{pp}(0, \frac{3}{2}\vec{k})\phi_{\pm}^d(\frac{3}{2}\vec{k}) + \mathcal{A}_{\pm}^{np}(\frac{3}{4}\vec{k}, -\frac{3}{4}\vec{k})\phi_{\pm}^d(0)] \quad (16)$$

for $\vec{k}' = -\vec{k}$. In eqs(15,16) $\mathcal{A}_{+}^{NN}(\vec{k}_f, \vec{k}_i) = \mathcal{A}_{70\frac{1}{2}}^{NN}(\vec{k}_f, \vec{k}_i)$ and $\mathcal{A}_{-}^{NN}(\vec{k}_f, \vec{k}_i) = \mathcal{A}_{8-1-\frac{1}{2}}^{NN}(\vec{k}_f, \vec{k}_i)$.

Calculations of the helicity amplitudes using deuteron wave functions generated by various realistic NN interactions show that they vanish for high momenta:

$$\phi_{-}^d(\vec{p}) = 0 \quad (17)$$

$$\phi_{+}^d(\vec{p}) = 0 \quad (18)$$

The node in $\phi_{-}^d(\vec{p})$ is strongly correlated to the node in the S-state wave function $u_0(p)$ and results from the decrease of the radial function before it changes sign. We find that

the solution of eq(17) occurs for $1.4fm^{-1} < p < 1.7fm^{-1}$ and is quite sensitive to the NN interaction used [12]-[16] to generate the deuteron wave function. This is shown in Fig.1, where $\sqrt{8\pi}\phi_-^d(p)$ is plotted in the region of interest. $\phi_+^d(\vec{p})$ is also expected to vanish, but at considerably higher momentum, near $5fm^{-1}$. However the predicted solutions are much less reliable since at these high momenta non-nucleonic degrees of freedom are important.

The most important term in eq.(15) is expected to be the one involving the T^{pp} matrix element[4, 5, 11]. Neglecting the latter, $T_{\pm}^{IA}(0^\circ)$ becomes proportional to ϕ_{\pm}^d and therefore changes sign at the solution of eqs(17,18). We then conclude that the main component of the total T-matrix element T_- (T_-^{IA}) changes sign for a momentum close to $3.fm^{-1}$, leading to the following two facts: i) in this region of momenta rescattering terms become competitive; ii) at a certain value of momentum T_-^{IA} will be exactly symmetric to the remaining terms, and the total matrix element T_- will have a node; its location depends strongly on the NN interaction used and as well as on the rescattering terms. The vanishing of T_- implies

$$T_{20}(0^\circ) = -\sqrt{2} \quad (19)$$

and the spin transfer coefficients all vanish. T_{20} reaches its minimum possible value because the polarized cross section for aligned deuterons along the z axis vanishes.

The present results show that in the $\vec{d}(\vec{p}, (pp)_0)n$ reaction with a colinear geometry there are only two independent T-matrix elements. Furthermore these matrix elements can be determined directly from measurements of the unpolarized cross section and spin correlation observables. This fact presents a considerable challenge to the theory of the reaction and should provide new information on the NN T-matrix elements and the deuteron wave function at high momentum. In particular T_{20} is predicted to reach a minimum value

for an incoming kinetic energy close to 410 MeV in the laboratory frame, i.e. a recoil neutron momentum of around $270 MeV/c$. The minimum in T_{20} corresponds to a node in T_- , which is related to a node in the deuteron helicity amplitude $\phi_-^d(\vec{p})$. Analogously, in the $\vec{d}(e, e'p)n$ reaction [17, 18], $T_{20}(0^\circ)$ is also predicted to reach the value $-\sqrt{2}$ for $\phi_-^d(\vec{p}) = 0$, neglecting the e-n scattering amplitude, final state interactions and other lower order effects.

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Figure caption

Fig.1 - The $\sqrt{8\pi}\phi_-^d(p)$ amplitude calculated with different NN interactions.

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